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Practice article

Dual closed-loop sliding mode control for a decoupled three-link wheeled mobile manipulator

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ABSTRACT

This paper presents a dual closed-loop sliding mode control strategy for a wheeled mobile manipulator with three-wheeled mobile platform (WMP) and three-link manipulator. The Euler-Lagrange method combined partially with the Newtonian method is applied to obtain full dynamic model and decoupled model is constructed in order to provide simple dynamic model for controller's structure to be simplified. Instead of the conventional velocity command trajectory based kinematic backstepping control method, a dual closed-loop control system is designed. A virtual velocity command based on sliding mode surface is generated in outer loop and the gap between a generated virtual command velocity and real velocity is compensated by an inner loop sliding mode controller. Outer loop helps to faster posture trajectory generation for locomotion of the WMP. Next, a finite-time sliding mode controller with an assumed feedforward dynamic gain method is designed for joint trajectory tracking for three-link manipulator by adding finite-time control terms in the designed controllers to obtain faster settling time and stronger robustness. The designed controllers were implemented into microprocessor connected to DC and dynamixel motor systems equipped in mobile platform and manipulator, respectively. Comparative simulation and experiment with a conventional sliding mode control show the effectiveness of the proposed dual closed-loop finite time sliding mode control scheme.

1. Introduction

Over the past decades, there have been many studies on wheeled mobile manipulators [1–7], which have become increasingly ubiquitous and are applied to several fields, including hazardous exploration, search and rescue, health-care, manufacturing, and entertainment. A wheeled mobile manipulator is comprised of wheeled mobility configuration and one or more robotic arms mounted on the mobile platform. The combination of platform mobility and arm manipulability increases the ability to perform dexterous robotic works that require both locomotion and manipulation compared to fixed manipulators. However, the configuration of kinematic and dynamic model is complex due to the coupling motion between the wheeled mobile platform (WMP) and manipulator. For kinematic posture control of the WMP, in many cases, the backstepping method [8–12] based on the reference velocity tracking viewpoint has been adopted with consideration of nonholonomic constraint condition. Thus, a desired position command is indirectly generated from the velocity command. This makes intuitive posture generation to be difficult except simple motion case. Depending on this velocity tracking method, when various motion configurations are required, it is difficult to obtain position command directly. If a direct and intuitive posture control command is adopted in the WMP control scheme, the generation of position trajectory can be conveniently and easily generated.

Recently, the dual closed-loop control method combined with sliding mode control (SMC) [13–17] has been developed in the aero vehicle control and servo systems [17] [18], where the kinematic and kinetic control loop were separated as the outer and inner loops, respectively and two loop controllers for each loop were constructed. By borrowing this concept, we apply this dual closed-loop SMC to posture control of the WMP system. As an outer loop control system, a kinematic control system is constructed such that a position reference command is directly chosen and virtual velocity command is designed to generate the target velocity of the dynamic controller of the WMP. Next, an inner loop controller is built such that coupling effect transferred from manipulator motion as well as the dynamic effect of mobile platform are compensated by a designed sliding mode controller. This control can provide more intuitive position tracking target and is more

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conveniently used in the WMP motion control than the conventional velocity command based backstepping posture control method [8–12].

Dynamics of the whole system including both three-wheeled WMP and three-link manipulator are modeled using Euler-Lagrange equation with consideration of kinematic and kinetic relations of each component. Next, decoupled dynamic equations are built to avoid heavy controller structure and make controller to be designed easily. The sliding mode controllers for each loop are designed and a feedforward model obtained from iterative parameter assuming process is considered in the controller to bypass complex parameters identification of the mobile manipulator system. For comparing with the proposed dual closed-loop finite-time SMC system, the conventional first-order sliding mode controller with dual closed-loop is designed. Moreover, by adopting robust SMC scheme with additional finite-time control terms, which guarantee faster settling time and stronger robustness in the mobile manipulator system, more robust control performance against uncertainty of coupling effect between mobile platform navigation and variation of manipulator working condition can be obtained. The stability analysis for the closed-loop system with these control terms is conducted and finite-time is induced by the finite-time control theorem [19,20]. Furthermore, unlike the conventional terminal SMC [21], a proposed finite-time control can void the singularity problem of the conventional terminal SMC without introducing the terminal sliding mode surface.

Next, the designed control systems were implemented into the designed ARM microprocessor control board combined with the mobile robot DC motor drive system and dynamixel motor system [22] in the manipulator to execute experimental performance verification.

The main contributions of this study are summarized as follows: 1) the full dynamic model of the wheeled mobile manipulator is constructed and its model is decoupled as two parts. 2) By generating virtual velocity command, an outer loop SMC is designed to provide more intuitive posture tracking trajectory of the WMP than the conventional velocity tracking method. 3) An inner loop robust sliding mode controller is designed to guarantee finite-time convergence with an assumed dynamic parameter method that can give fast controller design without depending on tedious parameter identification. 4) Faster convergence time and stronger robustness are obtained by only considering finite-time control terms in the designed sliding mode controllers.

Application examples of simulation and experiment were presented for verification of the proposed method with comparison of the conventional sliding mode control.

2. Problem formulation

2.1. Dynamic model of three-wheeled mobile manipulators

We made a three-wheeled mobile manipulator system as shown in Fig. 1. The mobile robot has three wheels with two driving wheel in left and right sides and passive wheel in the front part. The manipulator has three links and 3° of freedom, where each rotation axis is equipped with dynamixel motor. The dynamic equations of a three-wheeled mobile manipulator system are derived using the Euler-Lagrange equation according to the kinematics and force relations of Fig. 1. The derived dynamics are modified from the relationship of forces acting on the body and links, and constraints between the wheel and contact surface without considering the Lagrange multiplier method, which is used to solve the nonholonomic constraint problems of mobile robots. The variable of three-wheeled mobile manipulator are defined as follows: τ_r, τ_l, τ_1, τ_2, and τ_3 are the torque acting on two wheels, joint 1, 2, and 2, respectively, $\theta_r$and$\theta_l$are the rotation angle of the left and right wheel of the mobile platform; R and φ are the forward traveled position and the rotation angle of the mobile platform; $v$and$\omega$are the forward traveled velocity and the rotation velocity of the mobile platform; θ_1, θ_2, and θ_3 are the rotation angles of links 1, 2, and 3 with respect toz_0, z_1, and $z_2$axes; m_p, m_w, m_1, m_2, $m_3$are the mass of the mobile platform, wheel, link 1, and link 2; I_z and I_{zw} are the moment of inertia of the mobile platform and wheel with respect to z_0 axis; d is the distance between point P and wheels; $r$is the radius of the wheels; l_1, l_2,and $l_3$are the lengths of link 1, link 2, and link 3; and$r_2$and $r_3$are the distance between joints and the center of mass of the links.

Forces and torques acting on the body and each link are described in Fig. 2 and the tire dynamic relations are illustrated in Fig. 3 where $F_r$and$F_l$are the force interacting between the left and right wheels; $T_r$and$T_l$are the torque generated in the left and right wheels; $F_{fr}$and$F_{fl}$are the friction force interacting between the wheels and the contact surface. The position of C, the center of mass of the mobile platform are given as x and y. The position of the center of mass for two wheels are given by

$$x_r = x + d \sin \varphi,$$

$$y_r = y - d \cos \varphi,$$

$$x_l = x - d \sin \varphi,$$

$$y_l = y + d \cos \varphi, \tag{1}$$

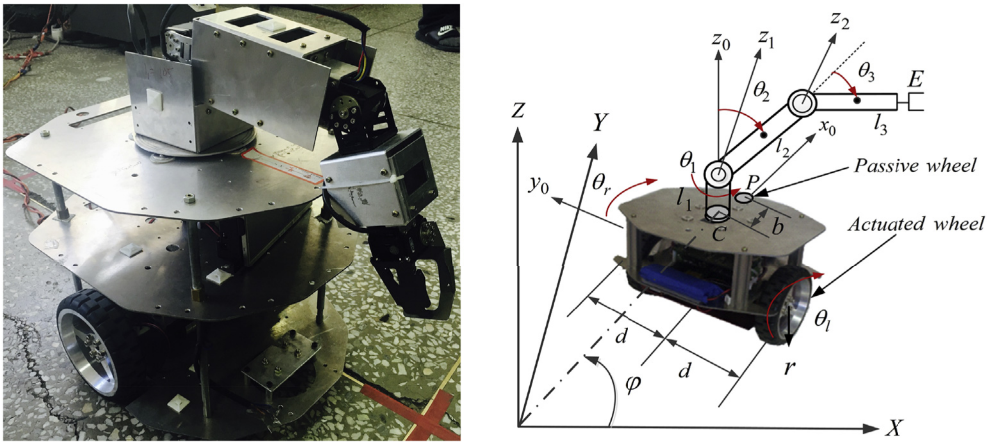

Fig. 1. Photograph and schematic description of the designed mobile manipulator.